

March 1999

MSUHEP-90315

Analysis of tbW and ttZ couplings from CLEO and LEP/SLC data

F. Larios^a, M. A. Pérez^b and C.-P. Yuan^c

^a*Departamento de Física Aplicada, CINVESTAV-Mérida
A.P. 73, 97310 Mérida, Yucatán, México*

^b*Departamento de Física, CINVESTAV
Apdo. Postal 14-740, 07000 México*

^c*Department of Physics and Astronomy, Michigan State University
East Lansing, Michigan 48824 , USA*

Abstract

We update the constraints on anomalous dimension four t - b - W and t - t - Z couplings by using CLEO $b \rightarrow s\gamma$ and LEP/SLC precision Z -pole data. It is found that the data imposes very stringent bounds on them. Moreover, the 2σ pull from SM predictions of A_{LR} (hadrons), A_b and $A_{FB}(b)$ have little chance of being explained by the strongly constrained anomalous couplings.

PACS numbers: 14.65.Ha, 12.39.Fe, 12.60.-i

1 Introduction

The mechanism of electro-weak symmetry breaking (EWSB) is still not known and until there is experimental observation of the scalar Higgs boson, the generation of masses for the W and Z bosons, and the fermions, will remain a mystery. If the mechanism that generates fermion masses is to be related to the EWSB, the interaction of the top quark, with a mass of $\sim 174 \text{ GeV}$ [1] (the same order as the EWSB scale $v = (\sqrt{2}G_F)^{-1/2} = 246 \text{ GeV}$), may reveal information on the EWSB sector.

In this work we update the constraints on dimension four anomalous couplings of the top quark with the gauge bosons by comparing the recent NLO calculation of the $B \rightarrow X_s\gamma$ decay rate with the most recent CLEO and LEP/SLC data. Furthermore, given that the forward-backward asymmetries of $Z \rightarrow b\bar{b}$ measured at LEP and SLC show a 1.8σ deviation from the SM prediction, we study the possibility of these anomalous couplings to explain such deviations.

2 Dimension Four Anomalous Couplings

The deviations from the t - b - W and t - t - Z couplings are considered in the context of the non-linear electroweak chiral Lagrangian, which is the most general effective Lagrangian that can describe decoupled or non-decoupled new physics effects [2]. Assuming no new physics effects in the neutral current bottom quark couplings, there are four coefficients that measure the deviation from the SM third family quark (top t and bottom b) and gauge boson (W^\pm and Z) couplings, they are defined as follows [2]:

$$\begin{aligned} \mathcal{L} = & \frac{g}{2c_w} \left(1 - \frac{4s_w^2}{3} + \kappa_L^{\text{NC}} \right) \overline{t}_L \gamma^\mu t_L Z_\mu + \frac{g}{2c_w} \left(\frac{-4s_w^2}{3} + \kappa_R^{\text{NC}} \right) \overline{t}_R \gamma^\mu t_R Z_\mu \\ & + \frac{g}{\sqrt{2}} \left(1 + \kappa_L^{\text{CC}} \right) \overline{t}_L \gamma^\mu b_L W_\mu^+ + \frac{g}{\sqrt{2}} \left(1 + \kappa_L^{\text{CC}\dagger} \right) b_L \gamma^\mu \overline{t}_L W_\mu^- \\ & + \frac{g}{\sqrt{2}} \kappa_R^{\text{CC}} \overline{t}_R \gamma^\mu b_R W_\mu^+ + \frac{g}{\sqrt{2}} \kappa_R^{\text{CC}\dagger} \overline{b}_R \gamma^\mu t_R W_\mu^- . \end{aligned} \quad (1)$$

In the above equation κ_L^{NC} , κ_R^{NC} , κ_L^{CC} , and κ_R^{CC} parameterize possible deviations from the SM predictions [2]. (t_L denotes a top quark with left-handed chirality, etc.) In general, the charged current coefficients can be complex with the imaginary part introducing a CP odd interaction. The decay process $B \rightarrow X_s\gamma$ depends on the real and imaginary parts of κ_L^{CC} and κ_R^{CC} , although the contribution from κ_L^{CC} is suppressed by m_b . Previous analysis of their allowed values have shown that these couplings could be large, even of order 1, but in a correlated manner [2]. A similar conclusion can be drawn from the partial wave unitarity bounds [3]. In this update we show that the correlation has become so tight that even a deviation of the SM t - b - W coupling of order 5% would require a similar deviation for the t - t - Z couplings in order to be consistent with the LEP/SLC data.

3 The right handed t - b - W coupling and $b \rightarrow s\gamma$

The latest measurement of the $B \rightarrow X_s\gamma$ branching ratio (Br) by CLEO collaboration [4] gives

$$\begin{aligned} \text{Br}^{exp}(B \rightarrow X_s\gamma) &= 3.15 \pm 0.35^{stat} \pm 0.41^{sys}, \\ \text{with} \quad &2.1 \leq E_\gamma \leq 2.7 \text{ GeV}, \end{aligned} \quad (2)$$

where E_γ is the energy of the decay photon. It is roughly a 20% reduction in the error and a 40% shifted mean value, which is closer to the SM prediction, as compared with the 1995 result [5]. There has also been an improvement in the SM prediction, in which the next-to-leading order (NLO) QCD corrections have been calculated to reduce the renormalization scale dependence [6].

Using the recent NLO calculation we can write the branching ratio in terms of the C_7 and C_8 coefficients at the scale of W boson mass M_W [7]:

$$\begin{aligned} \text{Br}(B \rightarrow X_s\gamma) \times 10^4 &= 1.355 - 6.67\text{Re}(C_7(M_W)) - 1.22\text{Re}(C_8(M_W)) \\ &+ 5.79|C_7(M_W)|^2 + 0.3|C_8(M_W)|^2 \\ &+ 2.75\text{Re}(C_7(M_W)C_8^*(M_W)), \end{aligned} \quad (3)$$

where the numerical factors were obtained using the pole masses of top and bottom quarks as $m_t = 174$ GeV, $m_b = 4.8$ GeV, and the strong coupling at the Z -mass scale to be $\alpha_s = 0.118$. Furthermore, the energy of the decay photon is required to be larger than $(1 - \delta)E_\gamma^{max}$ with $\delta = 0.125$, which corresponds to the experimental cut of the photon energy range. In Eq. (3), the magnetic and chromomagnetic dipole coefficients C_7 and C_8 are sensitive to the t - b - W coupling. At one loop level, they receive contributions from the type of new physics listed in Eq. (1) as [8]:

$$\begin{aligned} C_7(m_W) &= -(1 + \kappa_L^{CC}) \frac{1}{2(x-1)^4} \left[\frac{2x^2 - 3x^3}{2} \ln(x) + \frac{x-1}{12} (8x^3 + 5x^2 - 7x) \right] \\ &+ \frac{m_t}{m_b} \kappa_R^{CC} \frac{1}{2(x-1)^3} \left[\frac{2}{3} (2 + 3x \ln(x)) - \frac{x^3}{2} - \frac{3x}{2} \right] \\ &+ \left(-\frac{x^3}{2} + 6x^2 - \frac{15}{2}x + 2 - 3x^2 \ln(x) \right), \\ C_8(m_W) &= -(1 + \kappa_L^{CC}) \frac{1}{2(x-1)^4} \left[\frac{3}{2}x^2 \ln(x) + \frac{x-1}{4} (x^3 - 5x^2 - 2x) \right] \\ &+ \frac{m_t}{m_b} \kappa_R^{CC} \frac{1}{2(x-1)^3} \left[3x \ln(x) + 2 - \frac{3x}{2} - \frac{x^3}{2} \right]. \end{aligned} \quad (4)$$

Hence, the $B \rightarrow X_s\gamma$ branching ratio predicted by the effective theory (1) is:

$$\begin{aligned} \text{Br}(B \rightarrow X_s\gamma) \times 10^4 &= 3.07 + 280\text{Re}(\kappa_R^{CC}) + 2\text{Re}(\kappa_L^{CC}) + 5520|\kappa_R^{CC}|^2 \\ &+ 0.3|\kappa_L^{CC}|^2 + 79 (\text{Re}(\kappa_L^{CC})\text{Re}(\kappa_R^{CC}) + \text{Im}(\kappa_L^{CC})\text{Im}(\kappa_R^{CC})). \end{aligned} \quad (5)$$

It is important to note that the coefficients of the terms proportional to κ_L^{CC} are at least two orders of magnitude smaller than their κ_R^{CC} counterparts. Roughly speaking, only very high values of κ_L^{CC} (of order 1) would give a significant contribution. From the theoretical standpoint we don't expect such extreme possibility to occur because new physics effect would likely modify the anomalous couplings at loop level, hence, at the order of $1/4\pi$ or $1/16\pi^2$. For this reason, from now on we will restrict the possible values of κ_L^{CC} to be at most 0.2, and drop quadratic terms such as the ones in Eq. (5).

From the above results, we can use the recent result (2) from CLEO to set limits on the real and imaginary parts of κ_R^{CC} as:

$$-.0035 \leq \text{Re}(\kappa_R^{CC}) + 20|\kappa_R^{CC}|^2 \leq 0.0039 , \quad (6)$$

where, the 2σ deviation, that corresponds closely to 95% CL, was used. Since the coefficient of the quadratic term, which contains the contribution from $\text{Im}(\kappa_R^{CC})$, is 20 times higher than that of the single $\text{Re}(\kappa_R^{CC})$, we could imagine a case in which very high values (of order ± 0.02 , for instance) of the imaginary part would give a large contribution which could be counter balanced by another large and negative contribution from the real part. Such a situation in which the CP violating coupling would be one order of magnitude bigger than the CP even real part is very unusual, though possible. In Fig. 1, we display the correlated allowed region for $\text{Re}(\kappa_R^{CC})$ and $\text{Im}(\kappa_R^{CC})$ defined inside the solid lines. As to be discussed below, $\text{Im}(\kappa_R^{CC})$ can be better probed with other experimental observables. As for the information already given by the branching ratio of $B \rightarrow X_s \gamma$, we conclude that at the 2σ level

$$|\text{Re}(\kappa_R^{CC})| \leq 0.4 \times 10^{-2} . \quad (7)$$

3.1 Measuring CP violating couplings

A non-vanishing $\text{Im}(\kappa_R^{CC})$ would signal a CP-violation effect. What do we know about this CP-violating t - b - W anomalous coupling? So far, there is only one experimental measurement that gives us some information on $\text{Im}(\kappa_R^{CC})$, and that is the $b \rightarrow s\gamma$ branching ratio itself. As presented in Eq. (5) this branching ratio is already sensitive to a CP violating coupling, and some constraining region can be already set for $\text{Im}(\kappa_R^{CC})$ as is shown in Fig. 1. On the other hand, there can be another observable of the $b \rightarrow s\gamma$ process that can be used to measure CP violation in the t - b - W coupling. The following asymmetry has been proposed to measure CP violation contained in the $C_{2,7,8}$ coefficients [9]:

$$\begin{aligned} A_{\text{CP}}^{b \rightarrow s\gamma}(\delta) &= \frac{\Gamma(\bar{B} \rightarrow X_s \gamma) - \Gamma(B \rightarrow X_{\bar{s}} \gamma)}{\Gamma(\bar{B} \rightarrow X_s \gamma) + \Gamma(B \rightarrow X_{\bar{s}} \gamma)} \Big|_{E_\gamma > (1-\delta)E_\gamma^{\max}} \\ &= a_{27}(\delta) \text{Im}\left[\frac{C_2}{C_7}\right] + a_{87}(\delta) \text{Im}\left[\frac{C_8}{C_7}\right] + a_{28}(\delta) \frac{\text{Im}[C_2 C_8^*]}{|C_7|^2} , \end{aligned} \quad (8)$$

where C_7 and C_8 are given at scale m_b . As before, there is a dependence on the energy range of the photon. Following Ref. [9], we consider the asymmetry for $\delta = 0.15$, then

we have $a_{27} = 1.31$, $a_{87} = -9.52$, and $a_{28} = 0.07$. In terms of the anomalous charged current couplings the asymmetry reads as follows:

$$A_{\text{CP}}^{b \rightarrow s\gamma}(\delta = 0.15) = \left(31 \text{Im}(\kappa_R^{CC}) + 0.2 \text{Im}(\kappa_L^{CC}) + 1.2 [\text{Re}(\kappa_L^{CC})\text{Im}(\kappa_R^{CC}) - \text{Re}(\kappa_R^{CC})\text{Im}(\kappa_L^{CC})] \right) / |C_7|^2, \quad (9)$$

where

$$|C_7|^2 = |C_7(m_b)|^2 = (19.9\text{Im}(\kappa_R^{CC}) + 0.141\text{Im}(\kappa_L^{CC}))^2 + (0.319 + 19.9\text{Re}(\kappa_R^{CC}) + 0.141\text{Re}(\kappa_L^{CC}))^2. \quad (10)$$

Again, we can simplify the above equation by neglecting terms with κ_L^{CC} ; here too, the numerical coefficients of κ_L^{CC} are much smaller than those of κ_R^{CC} terms. We find that

$$A_{\text{CP}}^{b \rightarrow s\gamma}(\delta = 0.15) = \frac{\text{Im}(\kappa_R^{CC})}{0.0031 + 0.41\text{Re}(\kappa_R^{CC}) + 12.8|\kappa_R^{CC}|^2}. \quad (11)$$

Notice that indeed this asymmetry is quite sensitive to $\text{Im}(\kappa_R^{CC})$ which is consistent with the conclusion of Ref. [9] that left-right symmetric models can give large contribution to the asymmetry $A_{\text{CP}}^{b \rightarrow s\gamma}$. As shown in Fig. 1, this asymmetry can set very strong constraints on $\text{Im}(\kappa_R^{CC})$. For instance, if $A_{\text{CP}}^{b \rightarrow s\gamma}$ proves to be smaller than 25%, it would mean $\text{Im}(\kappa_R^{CC})$ less than 10^{-3} .

What about $\text{Im}(\kappa_L^{CC})$? As shown above, the $b \rightarrow s\gamma$ process does not make a good probe of the left-handed CP-odd t - b - W coupling. Nevertheless, there are other B-decay processes with a good potential to measure $\text{Im}(\kappa_L^{CC})$ in future B factories. For instance, the hadronic channels $B_d \rightarrow \phi K_s$ and $B_d \rightarrow \Psi K_s$ have been considered in Ref. [10] for B factories. We shall not discuss it further in this paper.

4 Top quark couplings and LEP/SLC data

The validity of the SM at the electroweak loop level has been established with a very high precision in the recent (and almost final) results from LEP and SLAC [11]. Except for the Forward-Backward asymmetry (A_{FB}^b) of the b-quark and the total Left-Right asymmetry (A_{LR}) of $Z \rightarrow f\bar{f}$, there is a 1σ or better agreement with the experimental data. In the light of the remarkable experimental achievement given by the accuracy of the measurements, and also the degree of precision in the SM predictions, this agreement would impose strong limits on the anomalous couplings of the effective Lagrangian in (1). In principle, the low energy effective theory can be applied to describe an underlying new physics dynamics with or without a Higgs boson, for simplicity, we assume that there exists a SM-like Higgs boson with mass of 70 GeV, which brings the SM predictions to an optimum agreement with the data [11, 12], and concentrate on the effect from the anomalous couplings of the top quark. We first consider all the data that is consistent with the SM prediction within 1σ ,

and use them to constrain the allowed values of the anomalous κ terms in Eq. (1) at the 2σ level. Then, we discuss the possible predictions on A_{FB}^b and A_{LR} produced by the constrained κ 's.

There are two observables of Z -pole physics that are particularly sensitive to top quark couplings as they are proportional to the top quark mass. These are the ρ parameter, and the b - b - Z vertex; directly associated to ϵ_1 and ϵ_b in the analysis by Altarelli, et. al [13]. The net non-standard contributions to the ϵ parameters are

$$\delta\epsilon_1 = \frac{3m_t^2 G_F}{2\sqrt{2}\pi^2} \left(\kappa_R^{NC} - \kappa_L^{NC} + \kappa_L^{CC} - (\kappa_R^{NC})^2 - (\kappa_L^{NC})^2 + (\kappa_L^{CC})^2 + 2\kappa_R^{NC}\kappa_L^{NC} \right) \ln \frac{\Lambda^2}{m_t^2}, \quad (12)$$

$$\delta\epsilon_b = \frac{m_t^2 G_F}{2\sqrt{2}\pi^2} \left(\kappa_L^{NC} - \frac{1}{4}\kappa_R^{NC} \right) \left(1 + 2\kappa_L^{CC} \right) \ln \frac{\Lambda^2}{m_t^2}, \quad (13)$$

in which only contributions proportional to $(m_t^2 \ln \Lambda^2)$ are kept [2], and the cut-off scale of the effective theory Λ is taken to be $4\pi v \simeq 3$ TeV [14]. Note that κ_L^{CC} contributes to ϵ_b up to this order only through the contribution proportional to κ_L^{NC} and κ_R^{NC} ; since we want to consider all possible values (within ± 0.2) of κ_L^{CC} we choose to keep it there. Given the above results we can then use the experimental values of the ϵ 's to constrain the theoretical predictions [12]:

$$1.54 \times 10^{-3} \leq \epsilon_1^{\text{SM}} + \delta\epsilon_1 \leq 5.86 \times 10^{-3}, \quad (14)$$

$$-8.32 \times 10^{-3} \leq \epsilon_b^{\text{SM}} + \delta\epsilon_b \leq -0.88 \times 10^{-3}, \quad (15)$$

where the minimum and maximum limits represent 2σ deviations from the central values of the experimental measurements. From Ref. [12] we recall the SM values for ϵ_1 and ϵ_b are: $\epsilon_b^{\text{SM}} = -6.5 \times 10^{-3}$ and $\epsilon_1^{\text{SM}} = 5.5 \times 10^{-3}$ for $m_t = 173.8$ GeV and $m_H = 70$ GeV.

Using the κ 's contribution as well as the SM values of ϵ_1 and ϵ_b given above we obtain the following inequalities:

$$-0.019 \leq (\kappa_R^{NC} - \kappa_L^{NC}) - (\kappa_R^{NC} - \kappa_L^{NC})^2 + \kappa_L^{CC} + \kappa_L^{CC^2} \leq 0.0013, \quad (16)$$

$$-0.33 \leq (\kappa_R^{NC} - 4\kappa_L^{NC}) (1 + 2\kappa_L^{CC}) \leq 0.1. \quad (17)$$

Although the above bounds does not take into account the strong correlation among the possible values of the ϵ 's, which is described by a 4 dimensional hyperboloid, it is instructive to find out at this level what is the implication from these two bounds. In general, the constraints to the ρ parameter imply an almost linear relation:

$$\kappa_L^{CC} \simeq \kappa_L^{NC} - \kappa_R^{NC}. \quad (18)$$

The purpose of keeping the quadratic terms in Eq. (16) is to verify that indeed their presence is not significant, provided we do not consider the highly unlikely possibility of very big deviations of the top quark couplings (above 20%).

To improve the above analysis, we have perform a 2σ fit of the κ 's to the LEP/SLC observables, which includes Γ_Z , σ_h , R_e , R_μ , R_τ , R_b , R_c , $A_{FB}(e)$, $A_{FB}(\mu)$, $A_{FB}(\tau)$, $A_{FB}(c)$, $A_{LR}(\text{leptons})$, $A_\tau(\mathcal{P}_\tau)$ and $A_e(\mathcal{P}_\tau)$ [11], as well as the m_W^2/m_Z^2 ratio [12]. We find that the linear relation of Eq. (18) is now very precisely established, as the remarkably narrow allowed regions of κ_R^{NC} and κ_L^{NC} shown in Fig. 2 sharply describe segments of lines with slope equal to 1. Therefore, we conclude that the LEP/SLC data have strongly constrained the anomalous couplings of Eq. (1). Even though one of them, κ_L^{CC} for instance, can take on any value (within 0.2), the two other couplings κ_R^{NC} and κ_L^{NC} are constrained to satisfy Eq. (18) and cannot be far off from the value of κ_L^{CC} itself.

Let us now consider the three LEP/SLC observables that show an almost 2σ deviation from the SM, namely A_{FB}^b , $A_{LR}(\text{hadrons})$ and A_b [11]. Could the t - b - W and t - t - Z anomalous couplings account for these discrepancies? In Fig. 3 we show the predicted possible values of A_{LR} and A_{FB}^b for the two values of m_t . (Recall that the CDF/D0 direct measurement gives [1] $m_t^{CDF/D0} = 173.8 \pm 5.0$ GeV, which combined with LEP/SLC data gives [11, 12] $m_t^{fitted} = 171.3 \pm 4.9$ GeV.) The 2σ experimental range of these asymmetries are shown by the dashed lines. For a given m_t , the solid lines define a very narrow region of predicted values coming from the allowed values of the κ couplings. For $m_t = 171.3$ GeV, the A_{LR} data prefers a negative $\kappa_L^{CC} \sim -0.04$, whereas A_{FB}^b favors a similar but positive value of κ_L^{CC} . On the other hand, for $m_t = 173.8$ GeV, A_{LR} would require $\kappa_L^{CC} \sim 0.15$, but again A_{FB}^b would need a different value of κ_L^{CC} (bigger than 0.2 in this case). If it turns out that m_t is about 172 GeV, then a value of $\kappa_L^{CC} \sim 0.1$ could explain both A_{LR} and A_{FB}^b . Such a value of κ_L^{CC} would not modify the M_W dependence on m_t given by the SM.¹

5 Conclusions

Inspired by the fact that no satisfactory proven mechanism for the breaking of the electroweak symmetry exists, and the fact that the top quark stands out as much heavier than all the other known elementary particles, we proposed a model in which the t - t - Z and t - b - W couplings depart from their SM values. The SM has been highly tested by the reasonably good measurements of rare decay processes, such as $b \rightarrow s\gamma$, by the CLEO collaboration, as well as by the precision data of LEP and SLC. This is reflected in the very stringent constraints on the top quark couplings. For instance, the measurement of $b \rightarrow s\gamma$ alone sets a constraint of less than 0.5% for the possible strength of a right handed t - b - W coupling (in terms of the SM $g/\sqrt{2}$ value) and even a 2% upper limit for the size of an imaginary CP odd part. On the other hand, the LEP/SLC data (even though they do not restrict all the anomalous κ terms since possible cancellations are allowed), impose strong correlations on κ 's so that if only one coupling, κ_L^{CC} for instance, is not zero, the others are forced to be of about

¹We have also checked that, for $|\kappa_L^{CC}| < 0.2$, the correlation between M_W and m_t is almost identical to the SM prediction.

the same order of magnitude. Also, given this strong correlation of the anomalous couplings, one can find out their precise prediction of the forward-backward b quark asymmetries of Z decay and left-right asymmetry A_{LR} . At present, there is a 1.8σ deviation of the experimental measurement from the SM prediction. It turns out that these anomalous couplings have little chance of predicting such discrepancy. To do so, two requisites have to be met: (i) κ_L^{CC} has to be of order 0.1, and (ii) the mass of the top quark should prove to be nearly 172 GeV. Fortunately, at the Run-2 of the Tevatron, it would be possible to measure κ_L^{CC} to $\sim 5\%$ accuracy via measuring the single-top production rate [15].

Acknowledgments

We thank H.-J. He, E. Malkawi, T. Tait and V. Gupta for helpful discussion. F.L. would like to thank Conacyt for support. C.P.Y. was supported in part by the NSF grant PHY-9802564. We also thank the Aspen Center for Physics for their hospitality. Part of this work was funded by the joint NSF-Conacyt project: *Tests of SUSY and Electroweak Chiral Lagrangians*.

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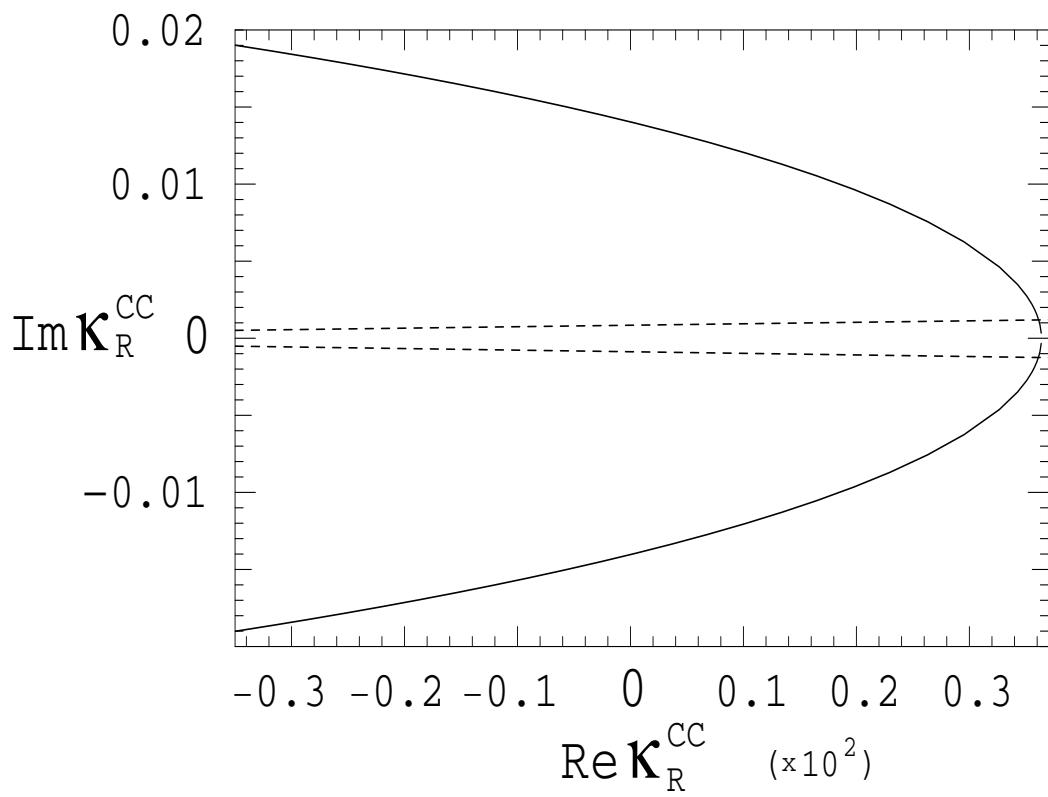


Figure 1: Allowed region for κ_R^{CC} from the measurement of the branching ratio of $b \rightarrow s\gamma$, between the upper and lower solid line curves. Region between dashed lines defined for the asymmetry $A_{\text{CP}}^{b \rightarrow s\gamma} \leq 0.25$.

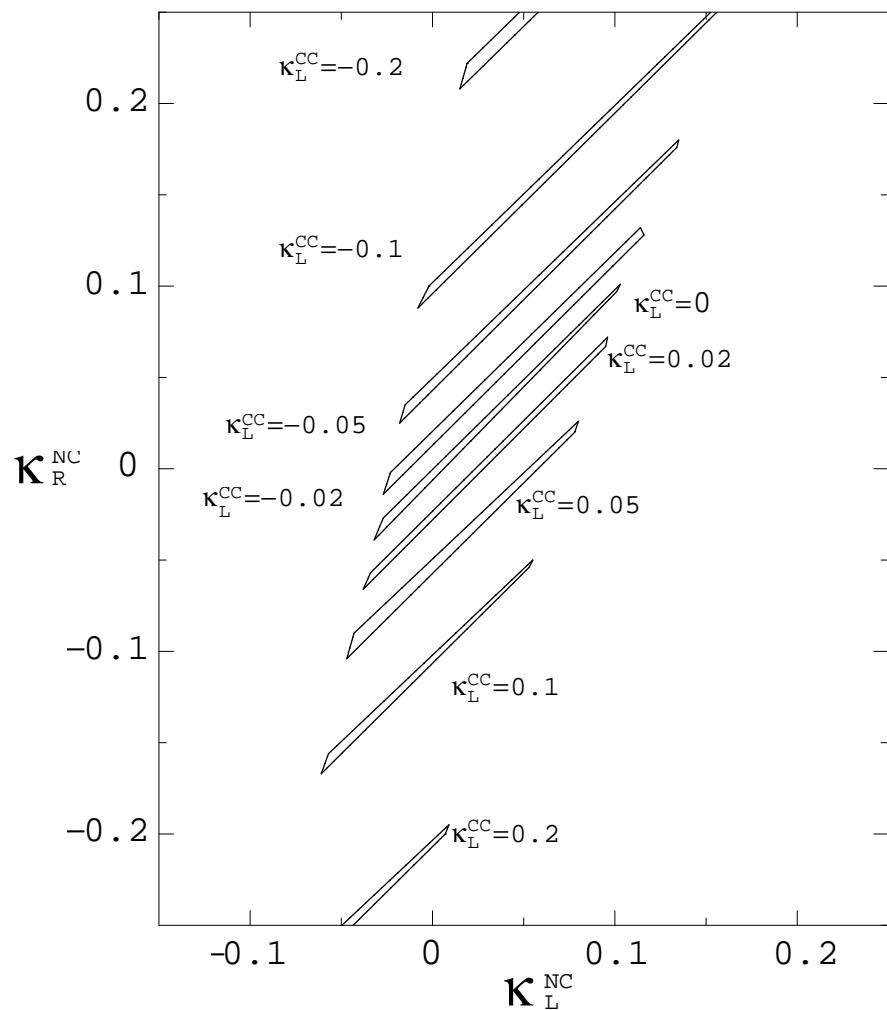


Figure 2: Allowed regions for κ_R^{NC} and κ_L^{NC} at different values of κ_L^{CC} .

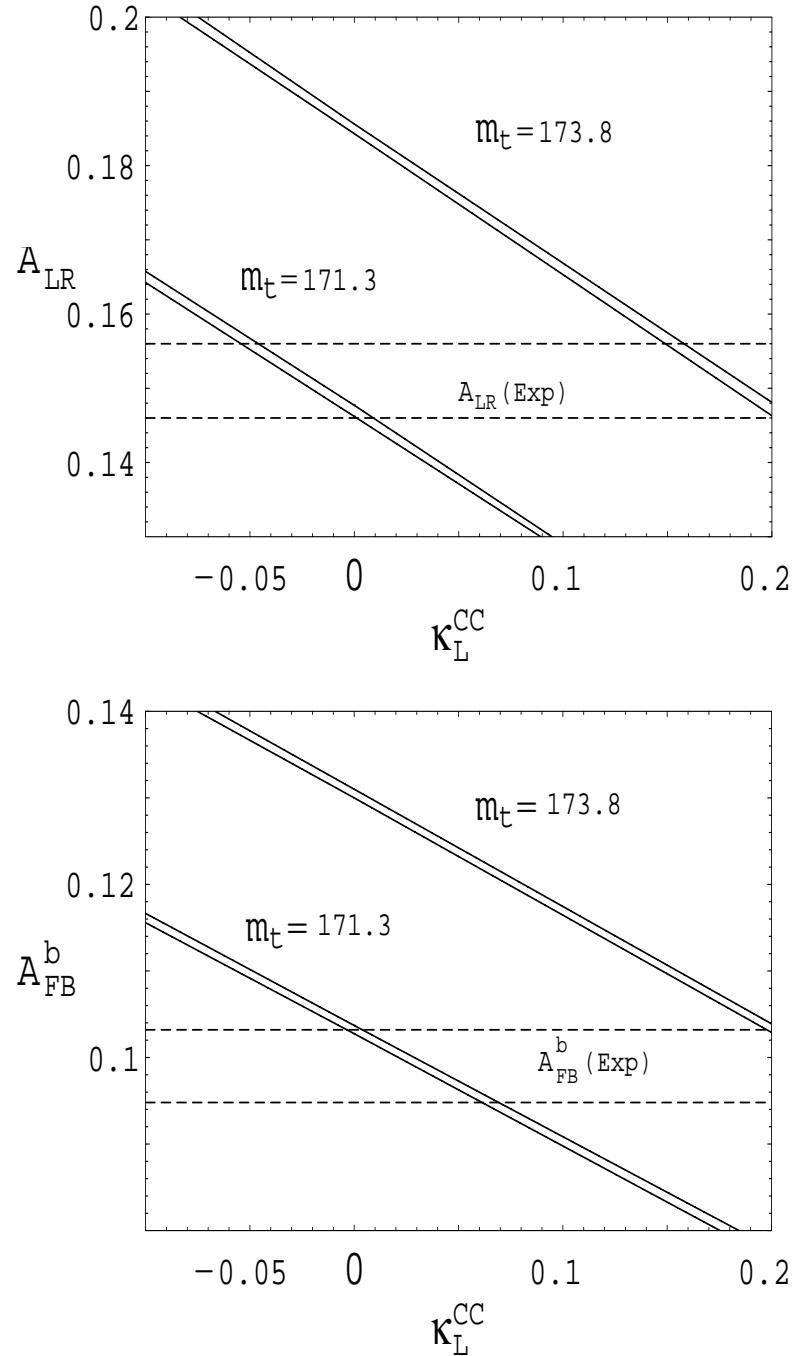


Figure 3: Asymmetries of Z decays as a function of κ_L^{CC} . The narrow regions between solid lines come from the small possible variation of the correlated κ_R^{NC} and κ_L^{NC} couplings.